national accelerator laboratory

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ACCELERATOR EXPERIMENT---A Search for Space Charge Tune Shifts in the Main Ring

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A variety of experiments have shown that the effective aperture in the Main Ring is about 1 cm wide at points where β = 9600 cm. This experiment was made to determine whether or not any Main Ring injection losses could be caused by the detuning of the machine by space charge fields within this narrow aperture.

To begin, I would like to give a very simple calculation for the space change tune shift for a circular beam of protons in free space. This will serve to determine the "order of magnitude" of the expected effect.

Consider a circular beam of protons having a charge density ρ and a current density $\sigma\beta$. The electric field at a distance r from the axis of the beam is $\vec{E} = \hat{u}_r 2\pi\sigma r$ and the magnetic field is $\vec{B} = \hat{u}_\theta 2\pi\sigma r\beta$. The force on a proton at a distance r from the axis of the beam due to the fields of the other protons is $\vec{F} = \hat{u}_r q2\pi\sigma r(1 - \beta^2)$. This is the same force that would be applied if there were instead an external magnetic field gradient

$$B' = -2\pi\sigma\frac{(1 - \beta^2)}{\beta}$$

Thus the effect of the fields of the other protons is to lower the betatron oscillation frequency. As the space charge fields move with the beam, the betatron oscillation frequency measured by stimulated coherent oscillations (pinging) will not be the actual oscillation frequency of the particles in the beam since it will not be affected by the space charge forces. For this reason, the tune shift caused by space charge forces is called "incoherent".

A rough estimate of the incoherent tune shift is

$$\delta\nu = \frac{1}{4\pi\beta\rho} B' \langle\beta\rangle \ell$$

$$\ell = \tfrac{1}{2} \times 2\pi \times 10^5 \text{ cm}$$

$$\langle\beta\rangle = 6000 \text{ cm}$$

$$\beta\rho = 3 \times 10^7 \text{ Gauss cm (8 GeV)}$$

The charge density is calculated with the assumption that the N particles are distributed in 900, 60 cm × 1 cm diameter, buckets in the Main Ring. For 2×10^{12} protons in the Main Ring, $\delta\nu = -0.075$. Because of the finely spaced betatron resonances, a tune shift this large should be a significant factor affecting the Main Ring injection losses.

The experimental technique used depends on an observation of the time dependence of the beam intensity when the operating point of the machine is set so as to be on the skirt of a sharp betatron resonance. If there is no beam intensity dependence of the tune, the beam decay should be exponential as is predicted by gas scattering out of a constant aperture. On the other hand, if there is a tune shift dependent on intensity, the decay will not be exponential and the curvature of the intensity function on a log plot will determine the tune shift.

In Figure 1, we show the 0.3 second transmission of the 8 GeV beam as a function of tune for $\nu_x = \nu_y$.

The experiment consists of observing the time dependence of the beam decay at each of the operating points A, B, C and D as shown in the figure. At Point B, where the aperture is independent of tune, the decay should be exponential as predicted from gas scattering regardless of any change in space charge tune shift as the current density in the beam decreases.

In Figure 2, we show the experimental data taken at Point B. (The intenisty detector is a radar IF amplifier with a log response connected to a pair of capacitive pickup plates. The amplifier was provided by Ed Higgins.) The beam intensity has decreased by a factor of 2 from 0 to 1.9 seconds. All of these data were taken with about 4×10^{11} protons/batch injected into the Main Ring.

The beam decay at Points A, C and D where the aperture is changing rapidly with tune is shown in Figures 3, 4 and 5. In Figures 3 and 5, the operating point is such that an increase in tune will increase the aperture. As there is negative curvature on the decay plot, the tune must be decreasing as the intensity decreases. In Figure 4, the operating point is such that an increase in tune will decrease the aperture. As there is positive curvature on the decay plot, these data also indicate that the tune is decreasing as the intensity decreases.

The experimental result that the incoherent tune increases with increasing intensity is in contradiction to the prediction of the calculation made at the start of this paper. In fact, the observed effects are very small and it would require a more through understanding of the RF system and the Main Ring magnet power supply to be certain that the observed effect is in fact due to space charge.

Summary

The space charge tune shift seen with 2×10^{12} protons accelerated in the Main Ring is very small and of opposite sign to that predicted by a simple calculation. If the booster intensity can be increased without an increase in emittance, the Main Ring accelerated beam intensity should increase in direct proportion to booster intensity.

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RFS:csn

MAIN RING 0.3 SECOND TRANSMISSION AT 8 GeV ($\nu_x = \nu_y$)

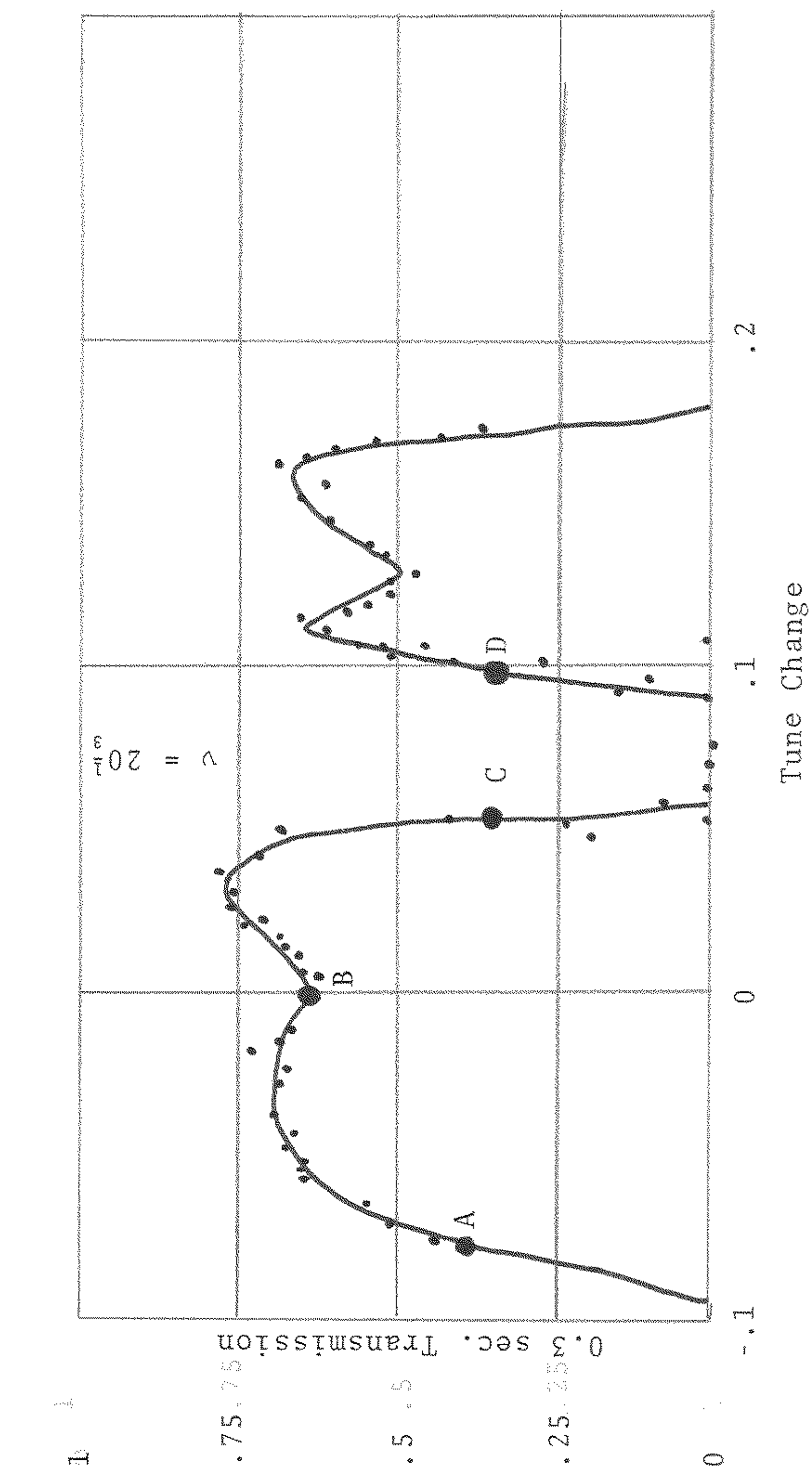

Figure 1.

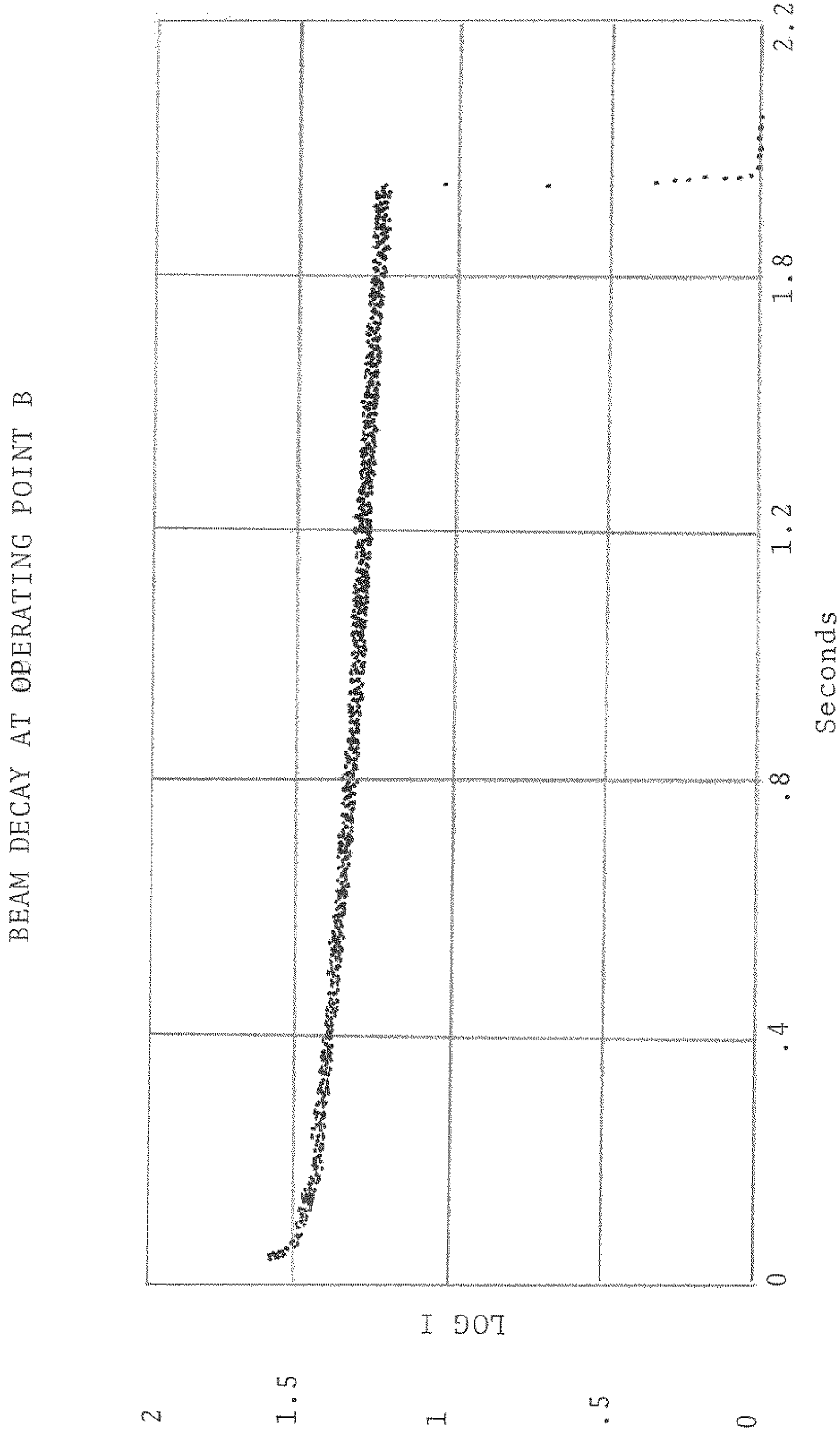
BEAM DECAY AT OPERATING POINT B
LOG I
2
1.5
1
.5
0
0
.4
.8
1.2
1.8
2.2
Seconds

Figure 2.

BEAM DECAY AT OPERATING POINT A

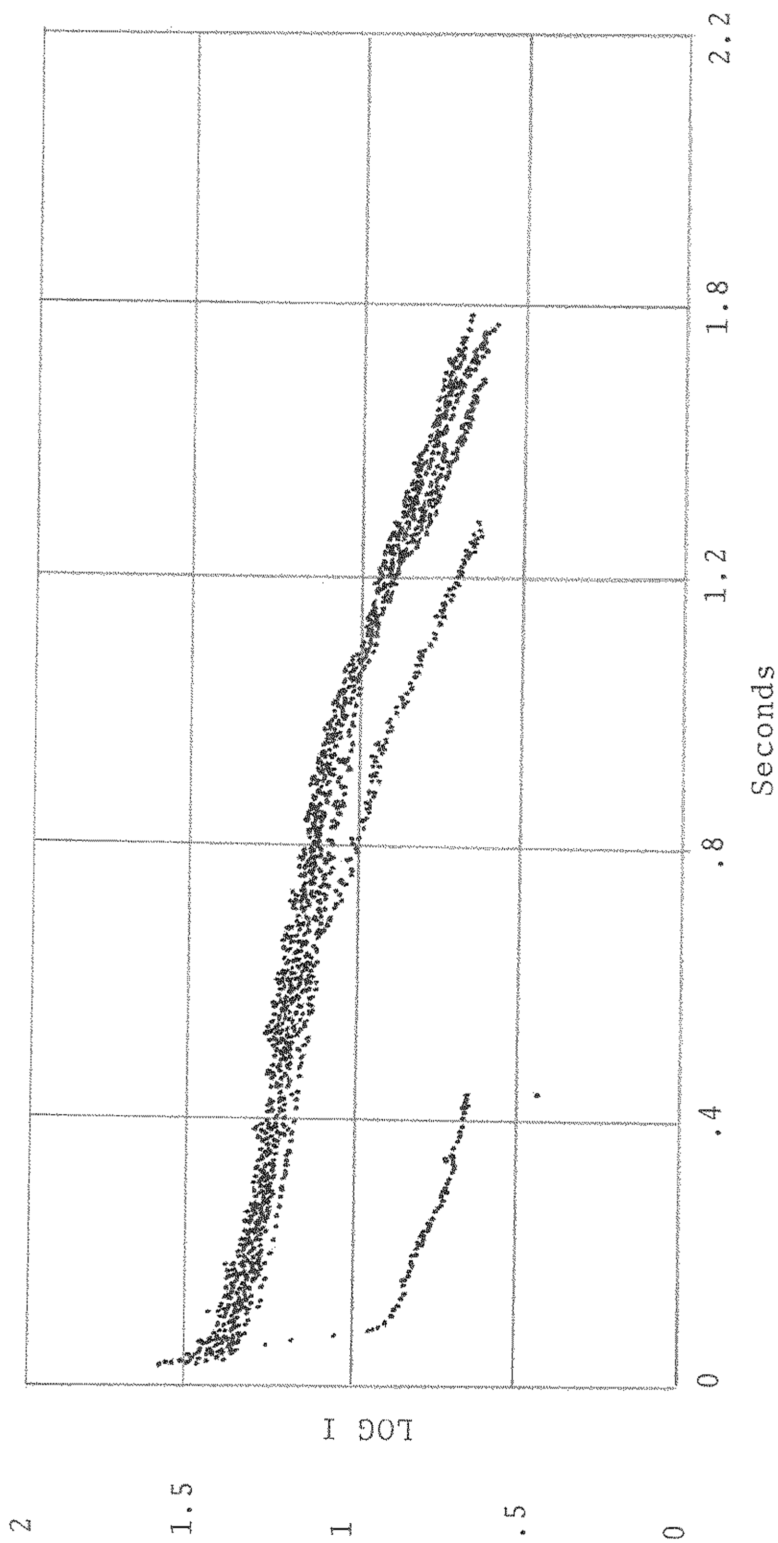

Figure 3.

BEAM DECAY AT OPERATING POINT C

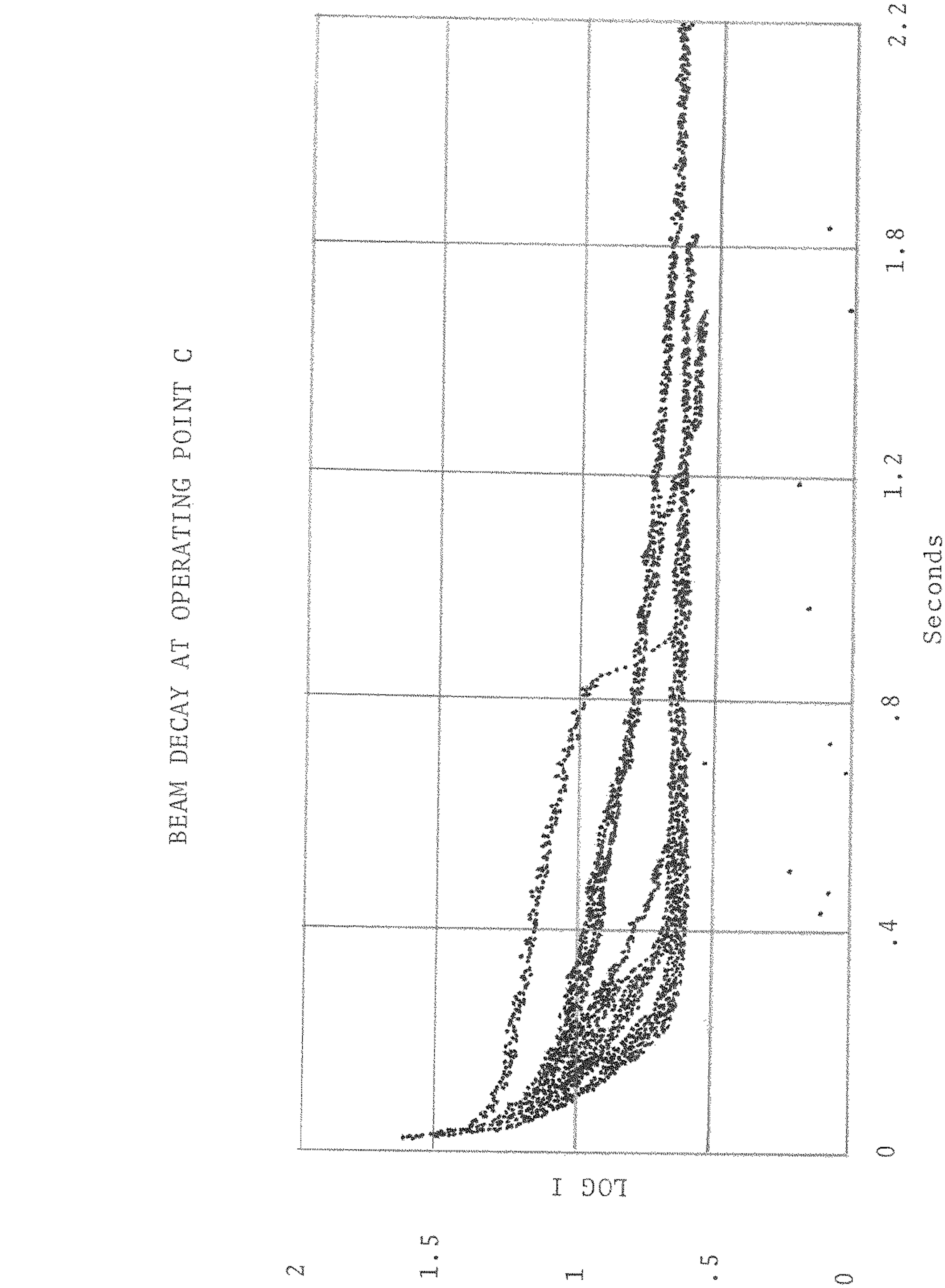

Figure 4.

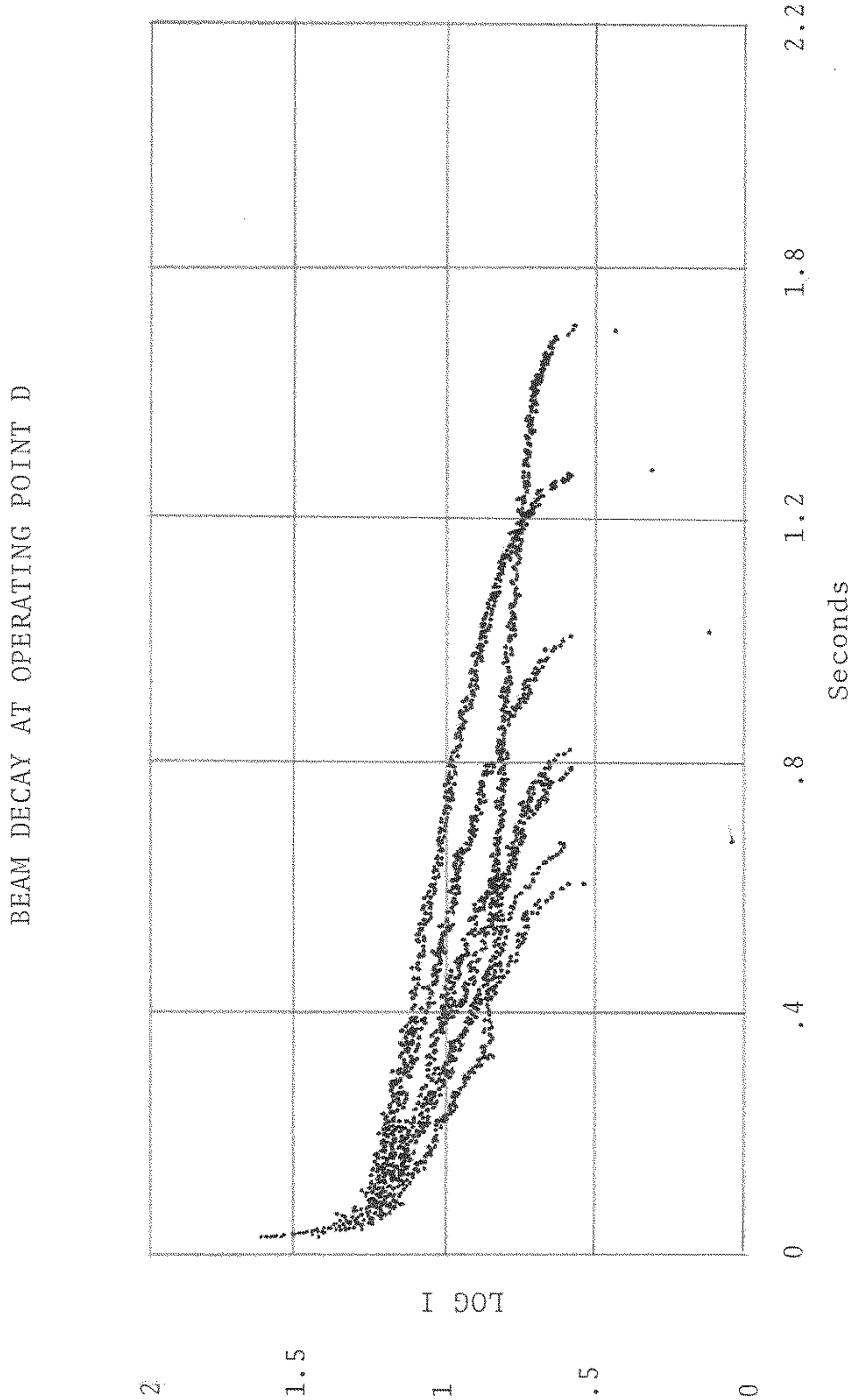
BEAM DECAY AT OPERATING POINT D
LOG I
2
1.5
1
.5
0
0
.4
.8
1.2
1.8
2.2
Seconds

Figure 5.